Vertical hydraulic gradient research in hyporheic zone of Beberibe river in Pernambuco State (Brazil)

Investigação do fluxo vertical da água na zona hiporreica num trecho do Rio Beberibe – PE

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ABSTRACT

The interaction between groundwater and surface water occurs naturally and is dependent on the dynamics in the hyporheic zone. The hyporheic zone is the interface between the surface water source and the phreatic aquifer and it's a system that also influences the water quality. An important feature is the ability to flux in this zone. This work aimed to evaluate the vertical hydraulic gradient in the hyporheic zone at two points in Beberibe river, Olinda-PE, to understand the hyporheic environment characteristics and water flow dynamics in experimental area, in addition to identify the existence of hydraulic connection between surface water and groundwater. The experimental phase consisted of infiltration tests in riverbed with cylinder infiltrometer and vertical hydraulic gradients readings with differential piezometer, complemented with grain size information, for an assessment of the water budget between the river and the aquifer. Analyzing the behavior of the interaction over the period of 10 months, it was observed that the Beberibe river (middle course) contributes to the groundwater recharge in most of the time. The average infiltration rate was 1.02 mm/min in point 1 and 0.85 mm/min in point 2. It was concluded that there is a variability in flow direction, which often is top-down, but may undergo change in the stream showing upstream after long periods of rainfall. Another conclusion is that grain size distribution of bed sediment, that is predominantly sandy, influences hydraulic conductivity of hyporheic zone and influences consequently the vertical flow rates.

Keywords: River-aquifer interaction; Infiltration; Cylinder infiltrometer; Differential piezometer; Hyporheic zone.

RESUMO

A interação entre águas subterrânea e superficial ocorre naturalmente e depende da dinâmica na zona hiporreica. A zona hiporreica é a interface entre o corpo hídrico superficial e o meio subterrâneo, sendo um sistema que também influencia a qualidade da água. Uma importante característica é a capacidade de fluxo nesta zona. O trabalho objetivou avaliar o fluxo vertical de água na zona hiporreica em dois pontos do rio Beberibe, Olinda - PE, para compreender as características do ambiente hiporreico e a dinâmica do fluxo de água nesta zona, além de identificar a existência de conexão hidráulica entre a água superficial e subterrânea. A fase experimental consistiu em ensaios de infiltração no leito com infiltrômetro de cilindro e leituras da diferença da carga hidráulica com piezômetro diferencial, complementadas com informações granulométricas, para uma avaliação da capacidade de transporte de volumes hídricos entre o rio e o aquífero. Analisando-se o comportamento da interação ao longo do período de 10 meses, verificou-se que o rio Beberibe no seu curso médio contribui para a recarga do lençol freático em boa parte do tempo, sendo a média da taxa de infiltração de 1,02 mm/min no ponto 1 e de 0,85 mm/min no ponto 2. Concluiu-se que há uma variabilidade no sentido do fluxo, que geralmente é de cima para baixo, mas pode sofrer alteração no fluxo apresentando ascendência após longos períodos de chuva. Concluiu-se, ainda, que a distribuição granulométrica dos sedimentos do leito, que são predominantemente arenosos, influencia a condutividade hidráulica da zona hiporreica e consequentemente as taxas de escoamento vertical.

Palavras-chave: Interação rio-aquífero; Infiltração; Infiltrômetro de cilindro; Piezômetro diferencial; Zona hiporreica.

INTRODUCTION

Groundwater and surface water interaction between rivers and streams is of great importance for both quantitative aspects of water and in environmental issues involving the whole food chain. The subject is very complex and related to a number of physical and biochemical factors, often requiring a multidisciplinary approach.

Surface water and groundwater resources are closely related and any work performed on one will ultimately affect the other (FEITOSA; MANOEL FILHO, 1997; ENVIRONMENTAL AGENCY, 2009). Given the importance of this, there has been a worldwide increase in studies and policies regarding surface water and groundwater interaction. This is also true in Brazil.

According to Sophocleous (2002), there is a growing increase in studies of vertical flow in river-aquifer interactions. In recent decades, many studies have focused on small-scale interactions between surface water and groundwater, also known as the hyporheic zone. This interface has become a very active research topic in many parts of the world (GENEREUX et al., 2008; LAUTZ; KRANES; SIEGEL, 2009; BOANO; REVELLI; RIDOLFI, 2010; BIANCHIN; SMITH; BECKIE, 2011; LARNED; DATRY, 2013; ALBUQUERQUE et al., 2014; LENCIONI; SPITALE, 2015). This zone is considered a region of great physical, chemical and biological dynamics, a very heterogeneous and active place, requiring continuous assessment.

The hyporheic zone, which is a transition zone of a few centimeters between a river and an aquifer, forms a unique dynamic ecosystem, which at the same time is influenced by, but may significantly influence, the flow and quality of groundwater (ENVIRONMENTAL AGENCY, 2009; LAWRENCE et al., 2013). Figure 1 shows an adaptation of a schematic diagram drawn up by the British Environmental Agency (ENVIRONMENTAL AGENCY, 2009) with many details concerning the hydrological, hydraulic, geological, chemical and biological processes.

Given the significance of this zone, it is extremely important to know its characteristics as one of the interaction zones of groundwater with surface water. This knowledge provides a way to understand these relations towards effective research on the vertical hydraulic gradient in the river-aquifer interaction.

The present report analyzes the vertical hydraulic gradient in a hyporheic zone where a field experiment has been carried on in the Beberibe River, in the state of Pernambuco - state in the Northeast of Brazil. An assessment of the carrying capacity of water volume between the river and the aquifer was assessed through infiltration tests and readings of water flow performed in the riverbed in order to understand the vertical flow of water in hyporheic zone.

The hyporheic zone and the dynamic of vertical flow

Many variables have been used to characterize the hyporheic zone, such as: ecological, morphological, chemical, hydrological, residence time and even combinations of these variables (WILLIAMS, 1989; BOULTON et al., 2010; GOOSEFF, 2010; BIANCHIN; SMITH; BECKIE, 2011; LARNED; DATRY, 2013; LEHR et al., 2015). The selected focus can influence the line of study, but the important thing is to understand that the hyporheic zone is a very dynamic environment, with an ecosystem responsible for a number of important reactions.

This report is made from the hydrological point of view, using the definition of Lewandowski et al. (2011) with the hyporheic zone as the saturated transition zone between surface water and groundwater, being a key terrestrial hydrosphere compartment.

A water flow study in the hyporheic zone has significant relevance as it may represent an opportunity to evaluate the effectiveness
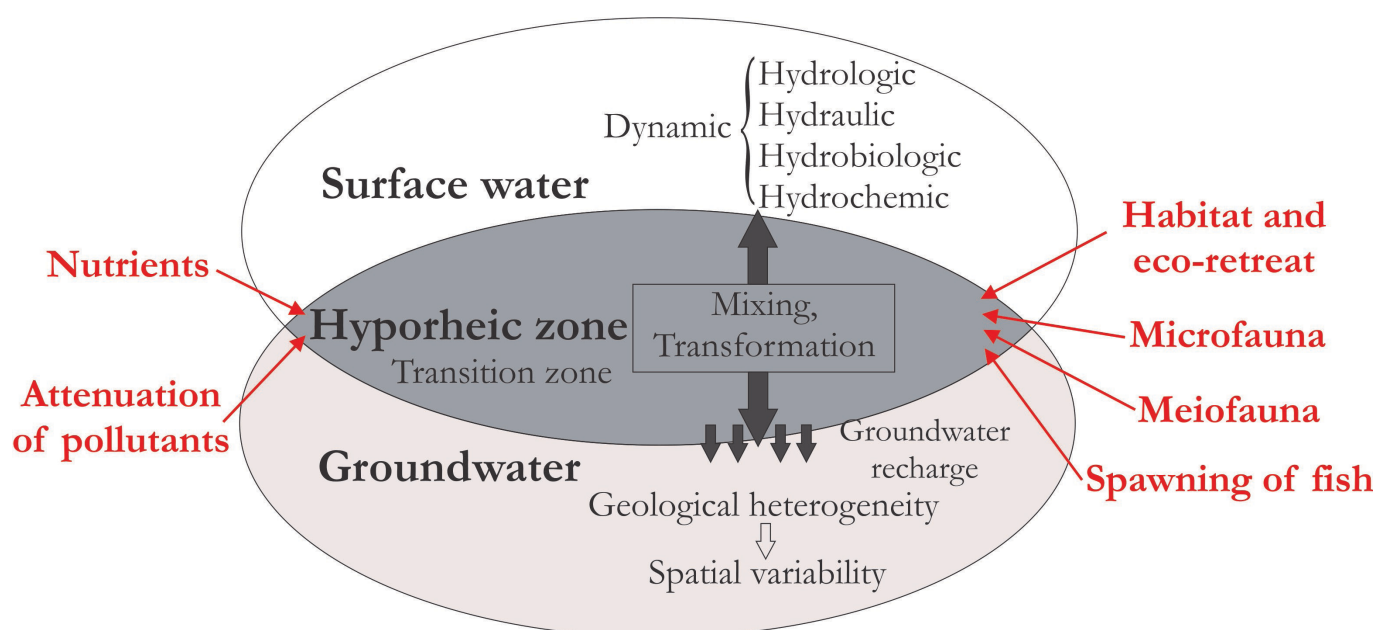

Figure 1. Scheme of hydroecologic functions and biogeochemistry of hyporheic zone and mixing zone and transition between surface water and groundwater. Adapted from Environmental Agency (2009).

of hyporheic zone in improving water quality or serve as a barrier against contamination of the aquifer (LAWRENCE et al., 2013).

The hyporheic flow can be altered by a variety of human activities, including those that change the flow or change the riverbed or the underground (BOANO; REVELLI; RIDOLFI, 2010; MAIER; HOWARD, 2011). Certain rainfall events can affect the surface water and have an influence on the subsurface flow.

Rainfall can indirectly influence the transverse variability of the river-aquifer interface, generating river runoff and sediment transport, intensifying this interaction. Consequently, there can be significant changes in surface or subsurface flow. Furthermore, precipitation events can generate the elevation of the aquifer levels by influencing the difference in hydraulic heads between the river and the aquifer (Figure 2).

In Figure 2, the A condition can be seen, when the water table contributes a q_1 flow into the hydraulic section due to the existence of a hydraulic head difference (Δh) between the aquifer and the main channel. In the B condition, soon after the rainfall, increased hydraulic head on the surface water is more significant than the increase in the hydraulic head in the aquifer. This is because the contribution from runoff in the river channel is faster than the contribution by infiltration into the aquifer. Thus, there is a contribution of the hydraulic gradient, making q_2 less than q_1. After a few days of a rain event, as in condition C, the aquifer will have received a considerable volume of water, thus causing an increase in the hydraulic head. The mainstream section, no longer receiving the contribution of runoff, is fed by the water table, thus causing a hydraulic gradient higher than under the A condition and therefore a greater flow q_3.
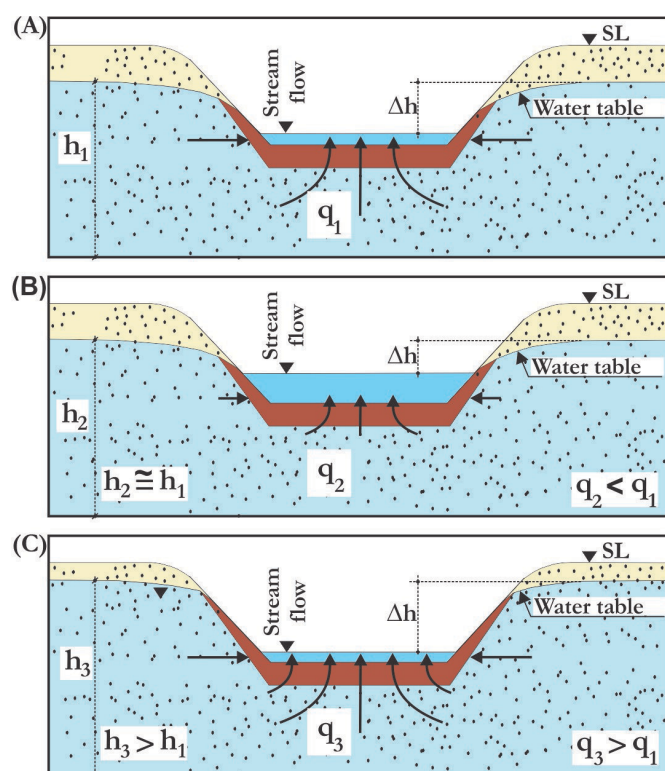
Figure 2. Aquifer interaction variability according to rainy season, situations: (A) early rain; (B) after the rain; (C) a few days later, after the rain. h is the hydraulic heads; q flow; and SL soil level.

Generally, rivers are evaluated by their distinctive interactions: influent, when the surface water contributes to the subsurface flow; or effluent, when the groundwater drains towards the river (PAIVA, 2009). This water exchange occurs through the hyporheic zone, where the flow is constrained and compounds are dumped directly into the downstream flow.

The water stream has its flow not only superficially but also through the interstices of the sediment flow channel and the riverbanks, thus creating a mixing zone between groundwater and surface water (KOBIYAMA, 2003). These mixing zones are also governed by the river level fluctuations.

The deposition of sediment on the bed can minimize hyporheic exchange (PACKMAN; MACKAY, 2003), since the retention of fine particles here reduces the occurrence or size of the pores that are formed in the soil that facilitate the process of interaction between surface and groundwater. This can cause riverbed clogging by a colmatation layer that also is influenced by chemical and biological processes.

The deposit of particles on a porous riverbed in the middle influences the permeability and cohesion of the sediment, thus limiting the infiltration capacity to the upper zone of the interstices (GOLDSCHNEIDER; HARALAMPIDES; MACQUARRIE, 2007; GUNKEL; HOFFMANN, 2009).

For this reason it is important to know the nature of the sediments involved in the system in view of the aspects of permeability and hydraulic conductivity that are essential for a better understanding of the vertical flow dynamics in the river-aquifer interface.

MATERIALS AND METHODS

Characterization of the study site

The research project area is located in the Metropolitan Region of Recife (RMR), on the border between the cities of Recife and Olinda, in the basin of the Beberibe river in its middle section (Figure 3).

According to the classification of river basins in the state of Pernambuco, the basin of the Beberibe river is part of Group 1 - GL1, which corresponds to the watershed group of small coastal rivers (APAC, 2014).

This group is located mainly on sedimentary rocks in the Pernambuco-Paraíba basin, where there are extensive tertiary deposits. Moreover, there are some quaternary formations created by alluvium and beach sediments.

From a meteorological point of view, according to APAC (2014), the average value of the cumulative annual total rainfall in the catchment area of the Beberibe river from 2003 to 2013 was about 2202.9 mm/year. This amount of rainfall is considered high, compared with other regions of northeastern Brazil.

In the region upstream from the BR-101 highway, one can easily observe the presence of local vegetation; downstream from the BR-101 highway, urbanization has taken over the basin of the Beberibe river, where currently there is only a small bit of native vegetation.

The catchment area of the Beberibe river today has a population that approaches the 590,000 mark, with the inhabitants
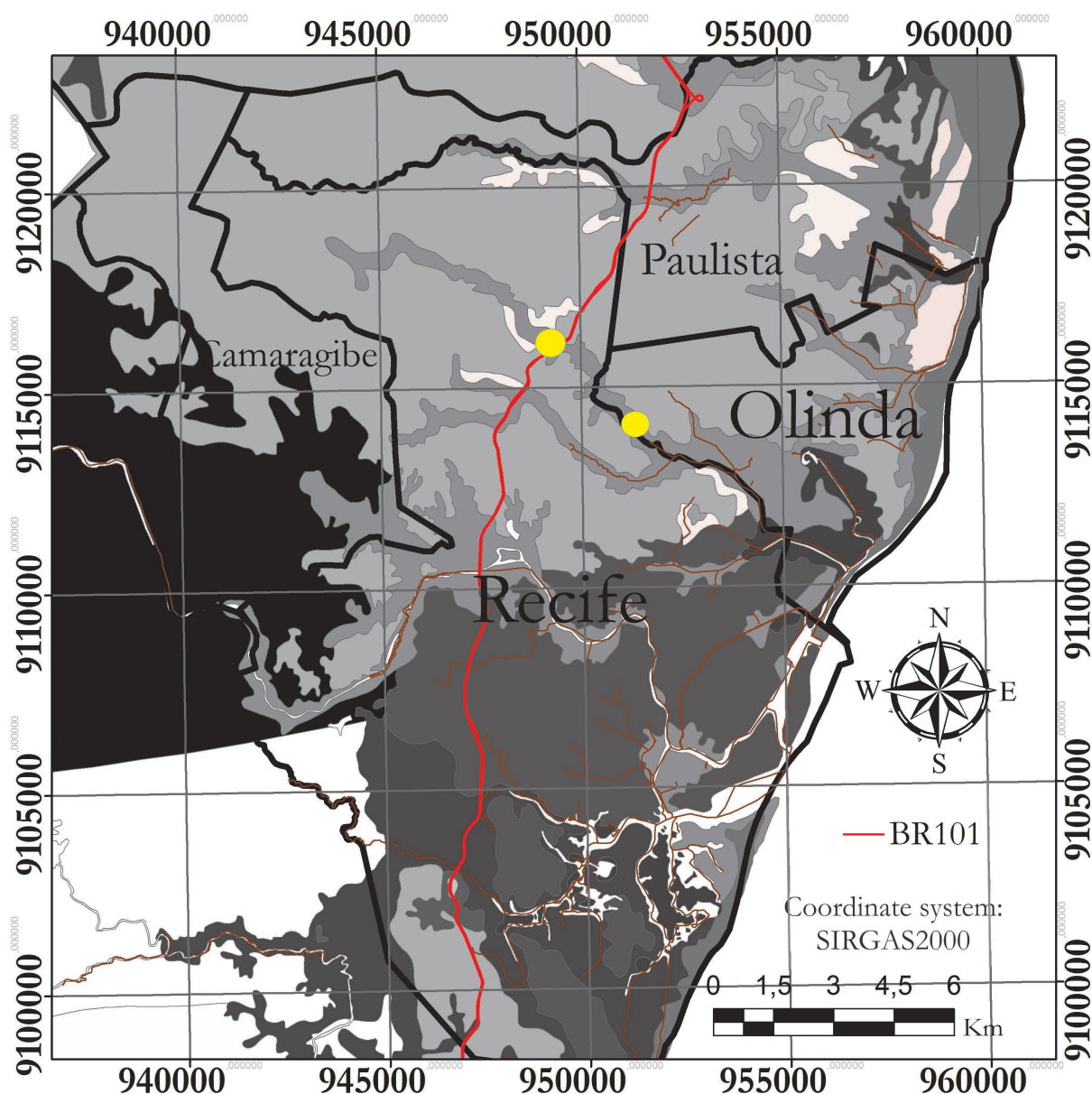
Figure 3. Study area location on Beberibe River banks on the border between Olinda and Recife. The yellow dots are the observation sites used in the study.

spread over its small area, making it into a predominantly urban and densely populated area, with about 7,300 inhabitants/km² (PERNAMBUCO, 2012).

No doubt, the Beberibe river is one of the most polluted rivers in the state of Pernambuco. In fact, informal settlements located near the slopes bordering the river have further ill-treated it.

Two points along the Beberibe River were chosen to estimate the vertical hydraulic gradient in the river-aquifer interaction (Figure 4).

Point 1 is located downstream from the BR-101 Highway, where the Beberibe river is approximately 6 m wide. There, the river flows through an urban area consequently suffering domestic pollution. The water depth varies from 0.30 to 0.40 m in dry and wet periods, respectively.

Point 2 is upstream from the BR-101 Highway, where the area is well preserved, with clear waters and no urbanization. At this point the Beberibe river has an average width of about 7 m and a water depth ranging from 0.20 to 0.25 m.

At selected points, infiltration tests were carried out to get data on the vertical hydraulic gradient and collect samples for particle size tests.

Grain size distribution

The river-aquifer interaction process can be greatly influenced by the characteristics of the soil that make up the hyporheic zone because, depending on material found, the hydraulic conductivity sediment may be affected.
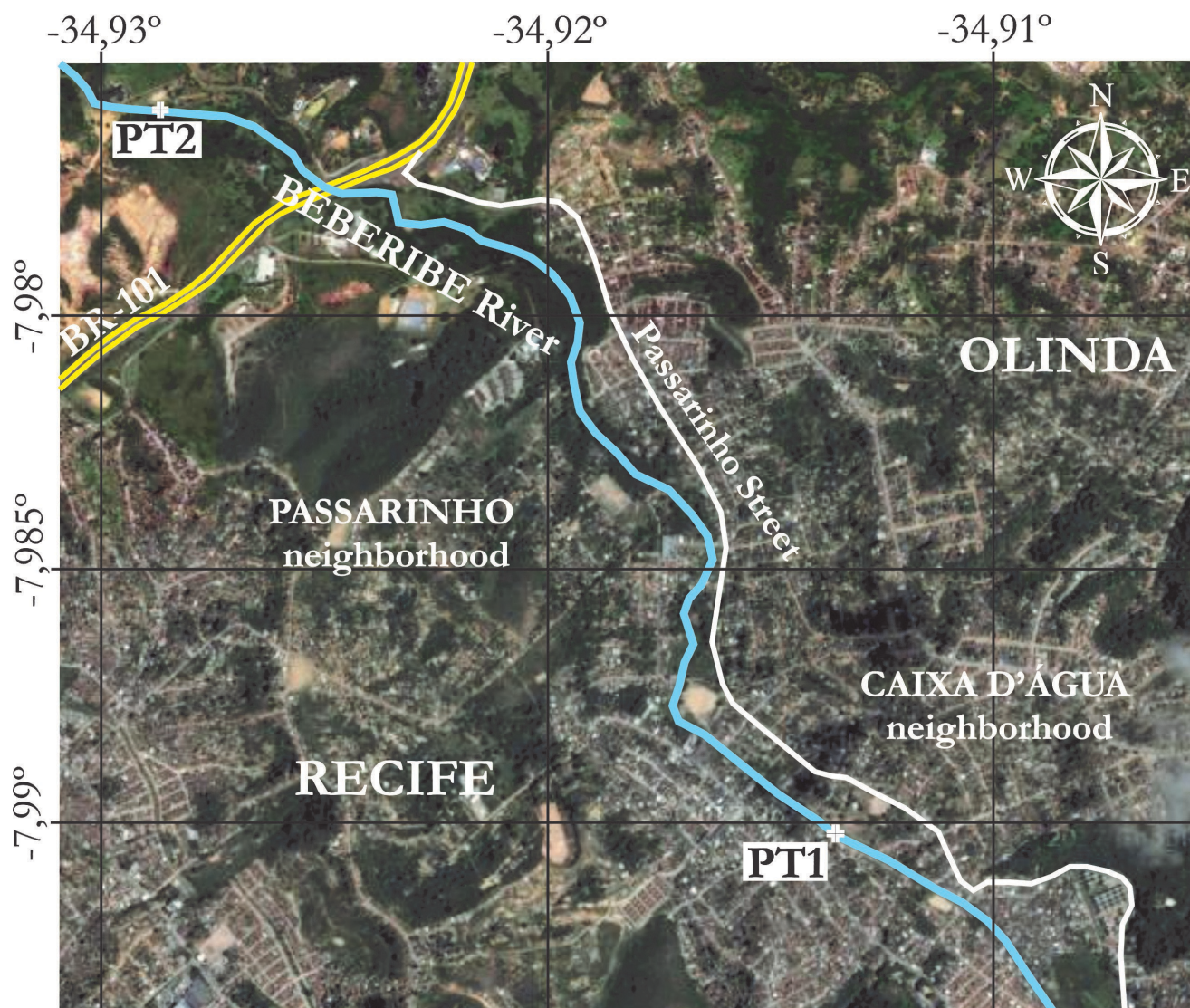
Figure 4. Locations of infiltration tests.

Towards understanding this, tests were performed to determine grain size distribution towards identifying the material that makes up the hyporheic zone analyzed stretch.

In November 2014, samples were collected for the grain size distribution test. It can be understood that these results were representative of the time intervals of the other observations of the study. In the study, at points (PT1 and PT2), samples from the hyporheic area were collected: 0-5 cm (1 sample for each point) and 5-10 cm (1 sample for each point). The samples are referred to as PT1 (0-5), PT1 (5-10), PT2 (0-5), and PT2 (5-10), total of 4 samples. The samples were collected with a sampler corer. All of the samples were taken from the riverbed axis and soon after collection were refrigerated for conservation.

Particle size analysis of the hyporheic sediments was processed at the Federal University of Pernambuco (UFPE) in the Geological Oceanography Laboratory (LABOGEO). The particle size distribution of the samples was determined by sieving and pipetting, as described by Suguio (1973) and ABNT (1984).

From the results obtained, the data of granulometric fractions were plotted on SYSGRAN version 3.0 software (CAMARGO,

2006), to determine the statistical parameters of the average diameter and the degree of selection, according to Folk and Ward (1957) equations and the triangular diagram from Shepard (1954). From the results it is possible to better understand the vertical hydraulic gradient behavior in hyporheic zone.

Infiltration tests

The infiltration quantification tests were performed every two weeks for 10 months from February to November 2014, allowing for a proper assessment of the vertical hydraulic gradient in hyporheic zone, since the tests were only carried out in the main channel of the riverbed.

To perform the infiltration tests, cylinder infiltrometers produced in acrylic were used, each cylinder with an area of $50.265\ cm^2$ and height 19.4 cm. Bags for water (hospital plastic bags) with a capacity of 2 liters were also used.

First about 4 cm of the open bottom of the cylinder had to be pushed into the hyporheic zone, done slowly until it

formed a column of sediment inside, thus stabilizing it in the underwater bed. Then between the instrument and the hyporheic sediment we applied a mixture of bentonite and water at a ratio of 1:1 along the external wall of the cylinder and the riverbed. Bentonite expands when it comes into contact with liquid and acts as a sealant, preventing water entry or leakage along the periphery of the cylinder.

After the instruments were in place, the plastic bags, filled with water, were weighed on an electronic scale and attached to the cylinder. They were put into the river under local environmental conditions such as temperature of the river, possible currents, water depth and the same hydraulic load (Figure 5).

After 20 minutes, the water bag was removed from the river and reweighed. The time of 20 min was determined by the research team, after several observations, to be enough to base the calculations on. At each point, there was the duplication of tests to confirm the results.

Based on this methodology, we sought to calculate the water infiltration rate in the bed by Equation 1:

$$I_t = \frac{V}{t.A} \qquad (1)$$

where: I_t = infiltration rate [mm/min]; V = volume of infiltration [mm³]; t = time [min]; A = cylinder area [mm²].

To improve accuracy, the amount of water from the water bag was measured in grams and the value subsequently transformed into mm³. for the calculation base, through its density, temperature of 25 °C was adopted, which was the average temperature measured at the site during periods of tests, with water density of 997 kg/m³ at that local ambient temperature.

To obtain data on weather conditions on the days of the tests and the previous days, rainfall data was collected from the nearest station to the research area (station 209 - Alto da Bondade) provided by Pernambuco Water and Climate Agency (Agência Pernambucana de Águas e Clima – APAC).

Hydraulic head reading

To read the vertical water flow in the Beberibe river, an instrument was developed at the federal university of Pernambuco - UFPE. The device, called a differential piezometer, has as its basic principle the use of a graduated scale (cm) to measure differences between the river water level and the hydraulic head of the riverbed.

The differential piezometer is simple to handle and easy to interpret. It is composed of two metal rods 1 meter high each. Inside each, there is a transparent plastic tube, which facilitates the determination of the water level by eye. The bottom of the device has a perforated 35 cm filter tip, to facilitate soil drainage. The tube is inserted here and passes the entire length of the rod.

At the test points, the device is pressed vertically into the bed to a depth of approximately 45 cm. When it is set into the hyporheic zone, the differential piezometer passes through the surface layer of the bed, where the water enters the tube, which enables a reading of the level (Figure 6).

Three possible conditions can be read from the difference between the stream surface water level and the water level in the
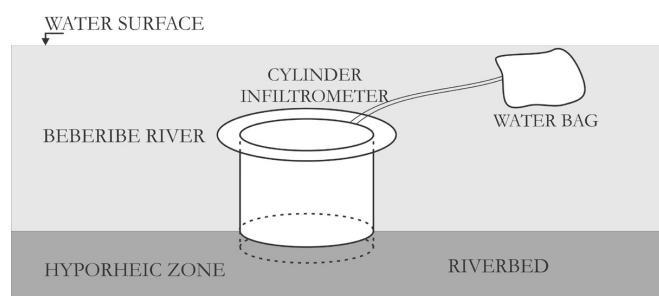

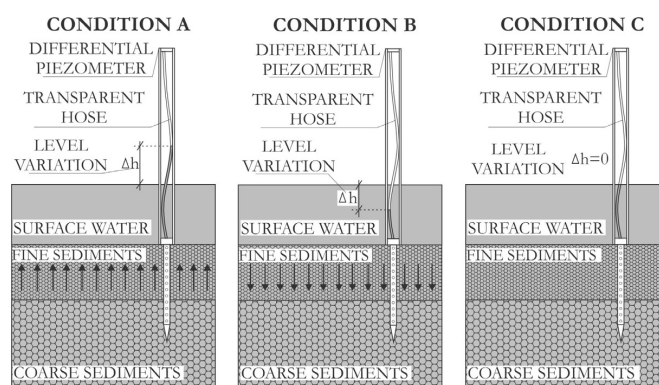**Figure 5.** Cylinder infiltrometer coupled to the water bag located in the river.

Figure 6. Interpretation of the differential piezometer under conditions of: (A) upflow; (B) downflow; (C) zero flow.

device: if the river water level is below the water level checked in the tube, it means that the river is being fed by the aquifer at the reading point (Figure 6A - upflow (+)); if the river level is above the water level displayed in the tube, it is possible to conclude that the river is feeding the aquifer (Figure 6B - downstream (-)); there is the possibility that the water in the tube and the river surface water are at the same level, featuring a point where there is no vertical hydraulic gradient (Figure 6C - no flow (0)).

We observed that 30 minutes was enough for the system to reach equilibrium, given the problem of agitation during the placement of the device into hyporheic zone. After that time, the reading vertical flow of the river could be carried out with greater certainty.

RESULTS AND DISCUSSION

Grain size distribution

The results of particle size variation in the samples collected from the hyporheic zone of the two points studied in the Beberibe river, are shown on Table 1, together with the other parameters discussed in this study (mean diameter and degree of selection).

Samples from Point 1 and Point 2 have a greater amount of sand in the composition, i.e. the studied stretch of Beberibe river is predominantly sandy. However, there is heterogeneity in the diameters of the particles, ranging from coarse to fine sand. The coarse sand fraction predominates in the hyporheic zone at

Point 1, independent of the depth analyzed; while at Point 2, the samples showed an enrichment of fine material in the deeper layer.

According to the data obtained, the degree of selection bias of particles in the Point 1 samples showed variation between moderate and poor. At Point 2, the samples showed no change in their level of selection, thus being classified as poor.

The particle size data gathered in the tests made with samples of sediments from the hyporheic zone were used for a better understanding of vertical hydraulic gradient behavior in hyporheic zone.

Infiltration test analysis

The results of infiltration tests are of fundamental importance for understanding the vertical flow of the river in the hyporheic zone.

Table 2 shows the results of infiltration rates at Point 1 and Point 2, the stretch of the Beberibe River under analysis, and a summary of the data used for the calculations.

The test showed that on April 10 there was the greatest infiltration rate in the hyporheic zone at both points: Point 1 was 1.73 mm/min and Point 2, 1.28 mm/min. The least water infiltration rate in the hyporheic zone at Point 1 took place on June 18 (0.27 mm/min). The least at Point 2 was 0.19 mm/min, registered in the tests performed on March 12.

With respect to volume of water infiltration into the hyporheic zone: Point 1 had a variation of 146.9 cm³; and the variation at Point 2 was 108.8 cm³.

Considering that the speed of water infiltration in hyporheic zone of the Beberibe River was the same in trials at both points, we can say that Point 1 had a slightly greater leakage than Point 2. The averages rates of infiltration and variations in water volume infiltration show that during the period when the infiltration tests were being carried out, there was a higher incidence of vertical hydraulic gradient in the hyporheic layer at Point 1 than at Point 2.

Similarly, Arantes, Chaudhry and Marcussi (2006) quantified the exchange rate between the river and the aquifer in the Ribeirão da Onça basin, located in the municipality of Brotas – in the state of São Paulo. They added, however, that the method (infiltrometer

Table 1. Particle size distribution analysis of samples from the bank and riverbed at two different depths in the studied points of the Beberibe river.

POINTS	PERCENTAGE (%)				CLASSIFICATION		
	Gravel	Sand	Silt	Clay	Shepard (1954)	Average Diam. (φ)	Degree of selection (φ)
PT1(0-5)	9.14	99.79	0.07	0	Sand	0.42 (coarse sand)	0.76 (moderate selection)
PT1(5-10)	16.27	83.59	0.14	0	Sand	0.44 (coarse sand)	2.05 (very poor selection)
PT2(0-5)	7.48	84.36	1.64	6.52	Sand	0.40 (coarse sand)	1.93 (poor selection)
PT2(5-10)	19.98	58.21	5.08	16.73	Sand	2.54 (fine sand)	3.81 (poor selection)

(φ) phi - negative logarithmic scale of base 2; Diam. - diameter.

Table 2. Infiltration test conducted in 2014 in hyporheic zone at the Beberibe river.

Date	POINT 1			POINT 2		
	Infiltration mass (g)	Infiltration volume (cm³)	Infiltration rate (mm/min)	Infiltration mass (g)	Infiltration volume (cm³)	Infiltration rate (mm/min)
11/FEB/2014	93.5	93.8	0.93	63.5	63.7	0.63
27/FEB/2014	156.0	156.5	1.56	107.5	107.8	1.07
12/MAR/2014	74.0	74.2	0.74	19.5	19.6	0.19
26/MAR/2014	74.5	74.7	0.74	66.5	66.7	0.66
10/APR/2014	173.5	174.0	1.73	128.0	128.4	1.28
24/APR/2014	115.0	115.3	1.15	101.0	101.3	1.01
08/MAY/2014	105.0	105.3	1.05	91.5	91.8	0.91
22/MAY/2014	121.5	121.8	1.21	114.5	114.8	1.14
05/JUN/2014	94.0	94.3	0.94	86.5	86.8	0.86
18/JUN/2014	27.0	27.1	0.27	25.0	25.1	0.25
10/JUL/2014	103.5	103.8	1.03	91.0	91.3	0.91
31/JUL/2014	97.5	97.8	0.97	78.0	78.2	0.78
14/AUG/2014	84.0	84.3	0.84	81.0	81.2	0.81
28/AUG/2014	79.5	79.7	0.79	66.0	66.2	0.66
18/SEP/2014	71.0	71.2	0.71	59.0	59.2	0.59
30/SEP/2014	141.5	141.9	1.41	121.0	121.7	1.21
09/OCT/2014	96.0	96.3	0.96	85.0	85.3	0.85
23/OCT/2014	127.0	127.4	1.27	114.5	114.8	1.14
07/NOV/2014	105.5	105.8	1.05	113.0	113.3	1.13
Average	102.0	105.8	1.02	113.0	113.3	0.85

and piezometer) they used was appropriate, but requires continuous care for its proper functioning.

Among the many variables that can influence the vertical hydraulic gradient through the hyporheic layer, possibly the grain particle size distribution may be responsible for the capacity of water flow between the river and the aquifer. The stretch of the Beberibe river under study is predominantly sandy, with heterogeneous particles. Similar results were reported by Lee (1977) and Rosenberry (2005) reported similar results, demonstrating the efficiency of a cylinder infiltrometer for the investigation of vertical hydraulic gradient in lakes with moderately permeable sediments in the United States.

Among the many variables that can influence the water flow in the hyporheic layer, the most likely is the size distribution of the particles at Point 2, as the cause of decreased water flow at the local interface.

According to the results of the particle size study already presented, Point 2 is made up of fine and coarse sands, i.e., there is a good distribution of sizes in the particle material, better for filling in the gaps and leaving less water course for water seepage.

Moreover, the composition of the hyporheic sediments at Point 2 has a greater amount of muddy materials (silt + clay) than those found at Point 1. This fact favors the clogging process, i.e., directly affects the drainage capacity of the porous material through which the flow occurs, this being another reason to explain the fact that infiltration rates are lower at Point 2.

Obstruction caused by very fine particles is important because it can be decisive in the variation of hydraulic conductivity (ROSENBERRY; PITLICK, 2009; VELICKOVIC, 2005).

Moreover, the occurrence of precipitation during the testing period also can be considered as a factor influencing the amount of water infiltration into the hyporheic zone.

During the tests, it was observed that in the rainy season, or days after a rainfall, most of the infiltration rates recorded were less than during periods of little or no rainfall.

Figure 7 graphically illustrates the values for the average of infiltration rates and the daily rainfall at Points 1 and 2 during the infiltration tests. This Figure helps in the analysis of water infiltration average rates during the rainy period.

Points 1 and 2 were monitored and analyzed. Figure 7 shows that there had been a certain change in the amount of water infiltration. When tested on days of rainy events. there was a decrease in the river's contribution to the aquifer due to the change in soil saturation, modifying the relationship of the hydraulic gradient. With decreasing precipitation, the groundwater level on the banks decreases and the river infiltration rate into the aquifer gradually increases again. When the rain returns, the infiltration volume of the river into the aquifer begins to decrease after a few days.

The data in Figure 7 only confirm that in times of greater rainfall the interaction between surface water and groundwater is altered because, depending on the intensity of the rainfall, the higher water table reduces the hydraulic gradient between the river and the aquifer, as already explained above.

Researchers around the world are continuing to investigate the thickness of the hyporheic zone layer, however, until the moment there is no methodology to quantify this with reliable field investigation.
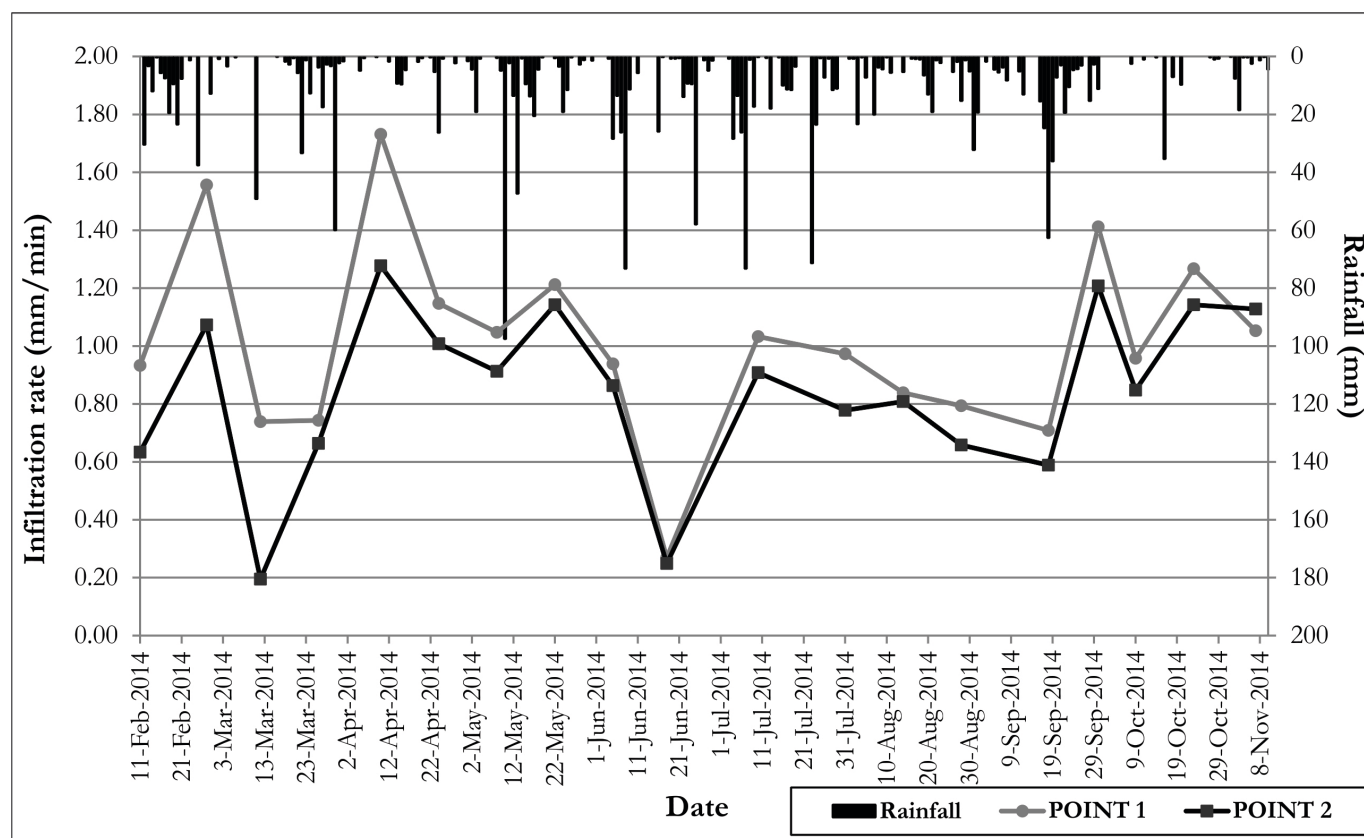

Figure 7. Precipitation and averages of infiltration rates at Points 1 and 2 along the Beberibe River.

The infiltration rates registered indicate that this stretch of the Beberibe river contributes to groundwater recharge in the aquifer, although it is not a great amount.

The cylinder infiltrometer facilitates the identification of major aquifer recharge areas, providing information needed for the sustainable use of water resources through the preservation of these areas.

Reading the difference of hydraulic head

The reading of the hydraulic head difference by the differential piezometer was performed in order to facilitate an understanding of the vertical flow in the hyporheic zone.

It is important to note that the direction of the vertical flow of the river is not always the same, according to Leek et al. (2009). They report that the hydraulic gradient can present spatial variation in its behavior at nearby locations.

For the Elkhorn River in Nebraska, USA, Chen et al. (2009) observed positive and negative values of the vertical hydraulic gradient between two locations only a few meters away from each other. Cheng et al. (2010) reported similar results in the Platte River in Nebraska.

Figure 8 shows a summary of the results of the variation of the vertical flow behavior at the points studied in the Beberibe River.

The reading 0.0 indicates a zero flow point, positive values indicate a point with upflow and negative means that the point is downflow.

Figure 8 shows that the two points analyzed exhibit a behavior change in their flow. This change occurs both temporally and between one point and another.

In relation to changes that occurred in reading the vertical flow between the points analyzed, it should be noted that Point 2 has a higher occurrence of zero flow than Point 1. This fact proves that there is a greater interaction between surface water and groundwater at Point 1 than at Point 2, regardless of the amount and direction of water flow.

The vertical hydraulic gradient between the aquifer and the Beberibe river presented three different behaviors. Possibly, the variations in readings that were found occurred as a result of rainfall events. It's known that the vertical flow behavior undergoes changes due to intense precipitation, which recharges the aquifer.

When rain is intense, it can cause saturation in the soil. When this happens, it is highly likely that the aquifer feeds the river in an upflow. In other cases, there is no flow in any direction, as characterizes a null flow.

From the results obtained with the reading of vertical flow, we could see that during rainy periods most of the flow in the hyporheic zone was a downflow or there was no flow. In times of drought, however, where there was flow, there was a greater water contribution in the river-aquifer direction. This fact can be explained by the increased groundwater recharge during rainy periods.

Even if the variation of sediment is uneven, a place with sediment particles of different diameters facilitates the clogging process. It is possible for the very fine particles to occupy the voids, significantly altering the permeability of the place In fact,
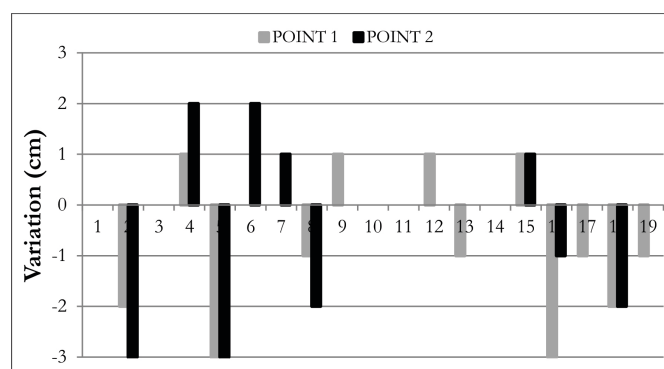
Figure 8. Fortnightly readings of the vertical hydraulic gradient on the riverbed of the Beberibe river in relation to the river surface water level in the period between 11/FEB/.2014 and 07/NOV/2014 (when the line does not appear, the flow is zero).
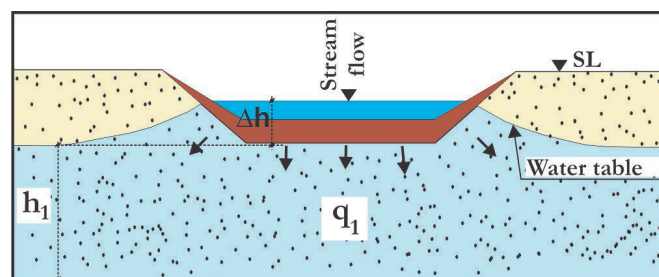
Figure 9. Interaction between surface water and groundwater - vertical hydraulic gradient into the aquifer, where the water is connected directly to hyporheic zone.

during the study the estimated vertical hydraulic gradient into hyporheic zone in Beberibe river, the relationship between the body of surface water and groundwater in most of the test areas had an influential condition characterized by surface water feeding the groundwater flow (Figure 9).

During the infiltration tests and reading of the vertical flow, it was observed that at the points studied in the Beberibe river there was a river-aquifer interaction. On days with higher precipitation, the water charge occurred through infiltration. But a few days after the rain, the amount of infiltrated water was smaller, because the soil was over-saturated (Figure 9).

The occurrence of infiltration in the riverbed provides the necessary moisture for riparian vegetation, in addition to the replacement of alluvial aquifers. When leakage occurs in the bed it means that there is a hydraulic connection between the aquifer and the river.

FINAL CONSIDERATIONS

Recently, there has been growing interest in river-aquifer interaction, and in this context, the hyporheic zone deserves attention as it is influential in this interaction.

The present study provided information on the transport of water volume in a stretch of the Beberibe river and the aquifer, enabling a better understanding of existing processes in the river-aquifer interaction along the Beberibe river banks, located in Recife / Olinda - PE.

The instruments used provided a better understanding of the process of infiltration / exfiltration in hyporheic zone of the Beberibe river stretch, and may be useful for the study of water flow at other sites.

Infiltration tests and the vertical hydraulic gradient readings performed in the field enabled a better understanding of the water exchange that takes place in the river-aquifer interaction in the Beberibe river stretch studied in this report. In some places the river contributes to the supply of the aquifer through the descending vertical stream, however, in some situations the flow rises after the occurrence of precipitation. The average infiltration rate in the tests was 1.02 ± 0.33 mm/min at Point 1 and 0.85 ± 0.30 mm/min at Point 2, featuring a larger river-aquifer influence at Point 1 than at Point 2.

The sandy feature found on the site enhances the percolation of water between the empty places in the sediment.

Rainfall can influence the intensity and direction of the hyporheic flow, with reduction of infiltration, when the previous weeks have been very rainy.

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Jaime Cabral: Development of the work methodology, analysis of river-aquifer interaction, writing and revision.

Anderson Paiva: Preparation of graphs and figures, interpretation and discussion of results, writing and revision.

Roberto Barcellos: Treatment of grain size data, interpretation and discussion of results related to hyporheic sediments.

Laércio Santos: Interpretation and discussion of results of differential piezometer.